MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

S-I-S mm-WAVE MIXERS AND DETECTORS

D. W. Jillie, H. Kroger, L. N. Smith and D. M. Shaw
Sperry Research Center, Sudbury, MA 01776

Final Report
Contract No. N00014-81-C-2525

SRC-CR-83-33
October 1983

DTIC
SELECTE
NOV 15 1983

A

Prepared for
NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375

╋SPERRY
RESEARCH CENTER

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD - A134762	3 RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) S-I-S mm-WAVE MIXERS AND DETECTORS		5. TYPE OF REPORT & PERIOD COVERED Final Report 19 Sept. 1982 - 18 Sept. 1983
		6. PERFORMING ORG. REPORT NUMBER SRC-CR-83-33
7. AUTHOR(s) D. W. Jillie, H. Kroger, L. N. Smith and D. M. Shaw		8. CONTRACT OR GRANT NUMBER(s) N00014-81-C-2525
9. PERFORMING ORGANIZATION NAME AND ADDRESS Sperry Research Center 100 North Road Sudbury, Mass. 01776		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		12. REPORT DATE October 1983
		13 NUMBER OF PAGES (36)
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

S-I-S Device Fabrication, mm-Wave Detectors, Superconductivity, Josephson Device,
Niobium Carbonitride, Mixer Chips, Niobium

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program is an effort to achieve the ultimate goal of fabricating refractory superconducting
S-I-S mixer devices for operation in mm-wave receivers in the quantum mode and in the 8-10 K
temperature range. The following progress has been made toward the above goal: (1) development of in-house capability of depositing niobium carbonitride films (NbC_xN_y) of device quality
with transition temperatures to ~ 16 K; (2) development of NbC_xN_y:aSi:Nb and NbC_xN_y:Ge:Nb
devices of very high quality; (3) fabrication and successful operation of niobium based S-I-S
mixer chips; and (4) fabrication and evaluation of aSi and Ge barrier all-NbC_xN_y devices.

DD $_{1\ JAN\ 73}^{FORM}$ 1473 EDITION OF 1 NOV 65 IS OBSOLETE

NbC$_x$N$_y$:Ge:Nb devices have been fabricated with chemical vapor deposited (CVD) polycrystalline arsenic-doped germanium barriers. The figures of merit for these junctions are: $J_o \sim$ 80-200 A/cm^2, I_oR = 2.2 mV, V_g = 3.95 mV, ΔV_g = 0.1 mV and $V_m \lesssim$ 48 mV. NbC$_x$N$_y$:aSi:Nb devices using a composite silicon barrier have been developed to yield $J_o \sim$ 80-500, I_oR = 1.9 mV, V_g = 4.1 mV, ΔV_g = 0.4 mV and $V_m \lesssim$ 70 mV. These excellent results indicate that both barriers are suitable candidates for devices fabricated with NbC$_x$N$_y$ counter-electrodes.

All-Nb S-I-S mixer chips were fabricated and sent to Goddard Institute for Space Studies to be evaluated. The noise temperature was $\sim$ 60 K and the conversion loss of 5 dB. These results are comparable to Pb alloy junction results. A second-generation mixer was designed by GISS.

TABLE OF CONTENTS

iii

LIST OF ILLUSTRATIONS

LIST OF TABLES

v

SECTION 1
INTRODUCTION

The work performed under NRL Contract No. N00014-81-C-2525 Mod. No. P00001 is described in this report. This work is an ongoing effort to develop all-refractory, high T_c mm-wave mixers operating at 8-10 K. Although this goal remains for the future, very significant progress has been made. Previous related work has been performed under NRL Contract No. N00173-80-0159, completed in September 1981; and N00014-81-C-2525, completed in September 1982.

The superconductor chosen as the basis of this work is NbC_xN_y. This material is reactive sputter deposited, which results in the B1 (rock salt) NbN structure in which carbon plays a significant rule in stabilizing the deposited film in this desired structure. The best films have $T_c \sim 16$ K, which is sufficient for device operation at 8-10 K. The majority of the NbC_xN_y used in this work was deposited at NRL by Dr. E. Cukauskas [1,2], and the vast majority of development work on these films was completed by Dr. Cukauskas. However, in order to expedite device development it was necessary to have an in-house source of NbC_xN_y, rather than continuing the shipping of wafers back and forth between SRC and NRL. Thus, during the previous contract an existing UHV system was adapted for NbC_xN_y depositions, and initial characterization runs were completed [3]. The best result obtained at that time was $T_c \sim 13.5$ K. The optical reflectivity was rather low, < 70 percent at $\lambda = 850$ nm, indicating poor quality in terms of potential device applications. This was corroborated by fabricating two of the best wafers into junctions using the aSi barrier and Nb counterelectrodes. The best devices were of S-I-S character, but with extremely large leakage currents.

During the previous contract a number of improvements were made in developing NbC_xN_y/aSi/Nb devices. These devices are a useful stepping stone towards developing all-NbC_xN_y devices. As a result of our ongoing Nb work the aSi/Nb upper interface/barrier combination is already very well controlled and of high quality. Thus attention can be focused on improving

-1-

the quality of the NbC_xN_y/aSi lower interface/barrier combination. It was found that using a low power sputter etch of the NbC_xN_y lower electrode resulted in increased I_oR and V_g due to reduced damage of the surface during sputter etching. In addition, the composite barrier that was found to be successful in reducing subgap leakage in all-Nb junctions was equally successful in reducing subgap leakage in NbC_xN_y/Nb junctions. Also during the previous contract some fabrications of all-NbC_xN_y junctions using the aSi barrier and the thermal oxidation variant of SNAP were done. The best result was junctions with a definite S-I-S character, but with a reduced gap and very high subgap leakage.

During this period, S-I-S mm-wave mixers were designed with the help of personnel at the Goddard Institute for Space Studies (GISS). Fabrication had begun, but no mixer chips had been completed and evaluated.

Significant progress has been made over the past year in all the areas reported above. In the next section, deposition of high T_c, device quality, NbC_xN_y films is described. Section 3 covers all Josephson device results. Of particular significance is the development of a chemical vapor deposited germanium barrier. This barrier was initially developed on NbC_xN_y/Nb junctions. Since the barrier is grown at $380°C$ it should be more stable than the Si barrier under high temperatures. This is important because the potential best NbC_xN_y counterelectrodes will probably have to be deposited onto a heated surface.

Section 4 covers S-I-S mm-wave mixer results. First generation chips were fabricated and evaluated at GISS, giving good performance. A second generation chip has been designed, but masks have not yet been procured for it. The last section concludes this report with some thoughts on remaining problems in the satisfaction of the overall goal of producing useful mm-wave detectors operating at 8-10 K.

-2-

SECTION 2
NbC_xN_y DEPOSITION

The evaluation of superconducting thin films per se is usually made by T_c, X-ray diffraction, resistivity, composition (typically using Auger electron spectroscopy), and residual resistance ratio. For our purposes, the most important aspect of film quality is the electrical characteristics of tunnel junctions fabricated using the film. Low leakage S-I-S tunnel junctions with a very sharp rise at the superconducting energy gap are essential for successful S-I-S mm-wave mixers that can operate in the quantum limit.

All the NbC_xN_y used in this effort prior to this report was deposited by Dr. E. Cukauskas at NRL. By all the measures of film quality mentioned above, including device quality, this material is excellent. Also, as the relevant conditions affecting the film quality have come to be understood, the reproducibility of the NRL films has improved. The major problem with this arrangement has been the time required to ship wafers between NRL and SRC. In addition, wafers are subject to increased contamination and breakage or loss during shipping. In order to shorten the total time required to fabricate NbC_xN_y devices, and to expedite progress in fabricating all-NbC_xN_y devices SRC decided, during the previous contract, to develop an independent NbC_xN_y deposition capability.

An existing ion-pumped UHV system was adapted for NbC_xN_y deposition. This system is shown schematically in Fig. 1. It is equipped with an 8" diameter niobium target and a 500 W rf power supply. The anode table can be heated. However, maximum heater power is not available for more than 15 minutes due to heating of the elastomer seals in the J-arm. A CTI CT-8 cryopump has been installed directly adjacent to the chamber. The ion pumps are normally valved off during operation.

The first NbC_xN_y films were made using no anode heating. This was an attempt to emulate NRL results for ambient temperature depositions.
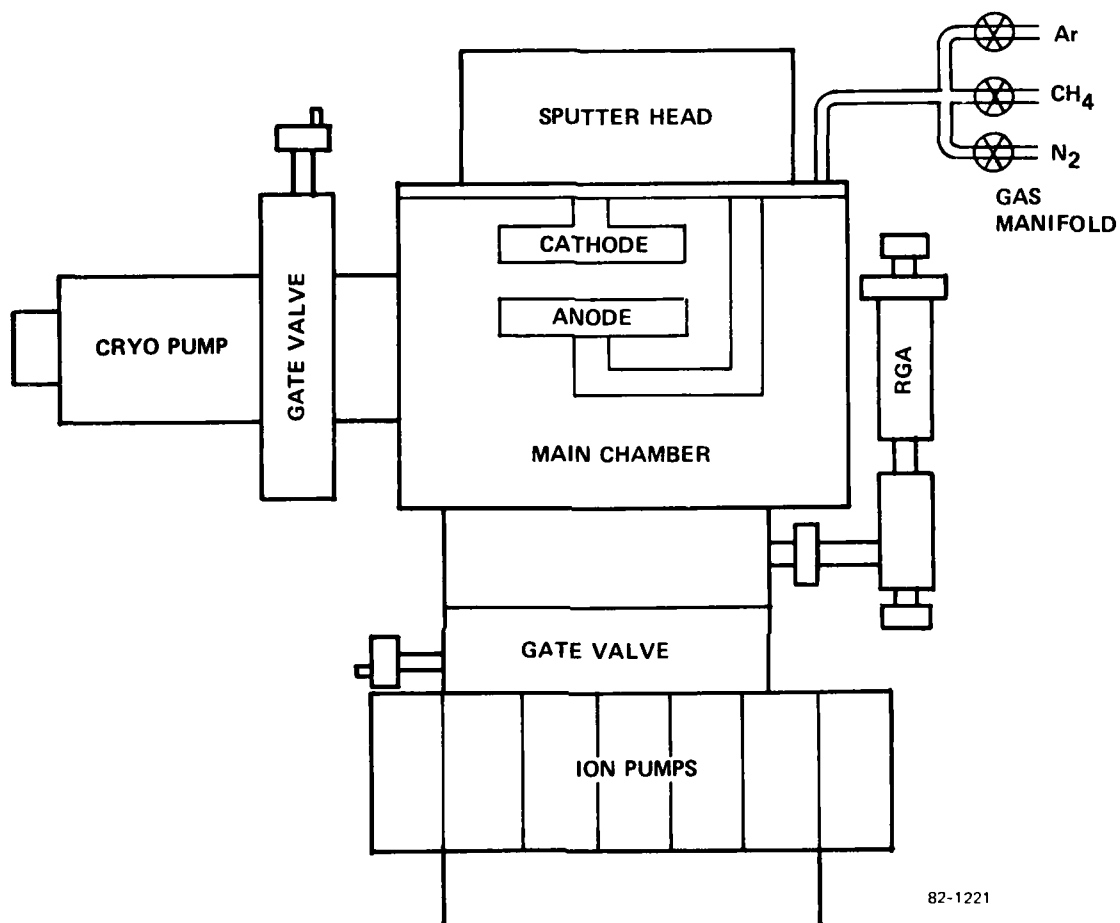
-3-

FIG. 1 A schematic diagram of the system used at SRC to deposit NbC_xN_y films. The ion pumps are typically valved off and not used.

It was subsequently found that the NRL "ambient" temperature was 425°C due to high rf power (1.5 kW) applied to a smaller 6" diameter cathode. Their best films deposited at this temperature had T_c = 15.6 K. Our best results were $T_c \sim$ 13.5 K. Also, the quality of junctions fabricated using our films was very poor, whereas NRL's ambient films yielded very good devices.

Since a larger rf power supply was not available, it was not possible to duplicate NRL conditions directly. Instead, the anode was heated to 200°C during deposition. This amount of heat could be sustained indefinitely by the system. The system parameters that produce the best films are indicated in Table I. These films typically have $T_c \sim$ 16 K and can be used to produce Josephson devices having low leakage and good overall quality. The NRL films are still slightly superior in terms of device quality, but the SRC films are more than adequate for device development. It is expected that the use of increased anode heat will yield better films. This improvement requires the installation of water cooling on the J-arm feedthrough.

The dependence of transition temperature on methane partial pressure is shown in Fig. 2 for SRC films deposited at ambient and at 200°C anode temperature. Also shown is the NRL "ambient" result, actually 425°C as mentioned above. The transition temperature at zero CH_4 partial pressure can fluctuate drastically, depending on the partial pressure of hydrocarbons in the system during deposition. This depends on system history. Typically, T_c will go down on successive depositions made with no methane as the system gradually "cleans" itself. Since the SRC and NRL systems are quite different, and different deposition parameters are used, the two results are not directly comparable. Nonetheless, it appears that there is a broad maximum in T_c at appropriate CH_4 pressures. Also, at higher substrate temperatures less CH_4 pressure is required to achieve high T_c films.

A few of the SRC films have been examined by Auger electron spectroscopy. The Auger system was not accurately calibrated. However, the best films show relatively large amounts of carbon. Our estimates would indicate a composition of Nb_2CN. This is consistent with NRL's result of $NbC_{0.4}N_{0.6}$ for their best "ambient" films. The role the carbon plays in

-5-

TABLE I

Parameters for Deposition of the Best

NbC_xN_y ($\sim$ 16 K T_c) Films in SRC's System

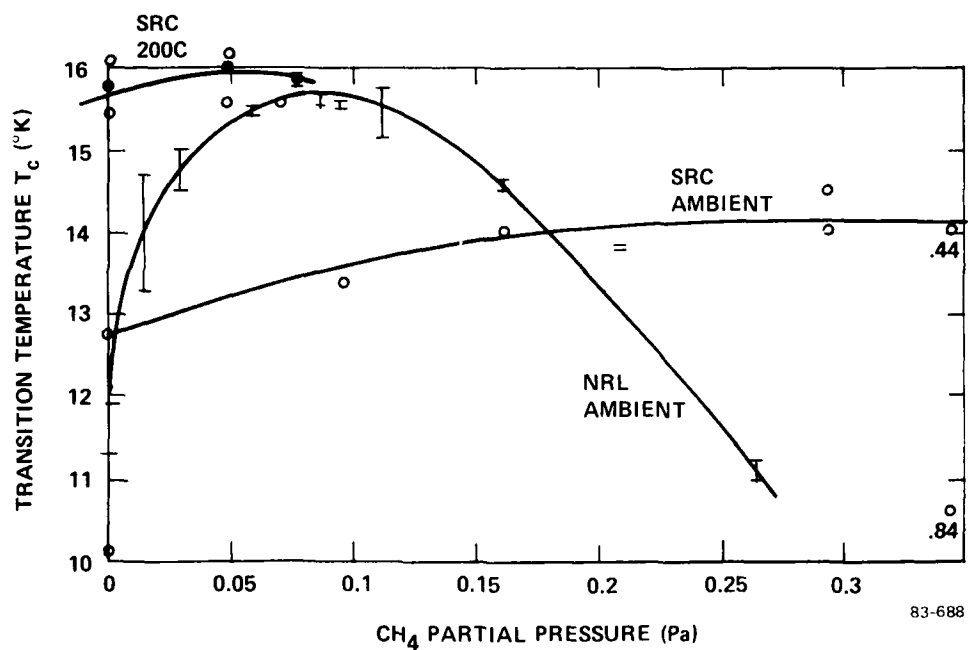| Ar Pressure	CH_4 Pressure	N_2 Pressure	Time	Power	Heating
9.24 μ	.05 μ	.71 μ	30 Min	500 W	200° C Minimum

FIG. 2 The transition temperature as a function of methane partial pressure of NbC_xN_y films deposited at NRL "ambient" conditions (actually 425°C), SRC ambient conditions, and SRC heated (200°C) conditions.

-7-

these films is not completely clear at this time. X-ray diffraction results indicate a mixed (111) and (200) orientation, with lattice parameter consistent with the fcc B1 structure. Given that the ratio of (C + N)/Nb is about 1 for all the better films it is reasonable to assume that carbon simply replaces the nitrogen in the B1 structure.

Optical reflectivity data from 200 nm to 900 nm wavelength are routinely taken on all our films. The rationale for this procedure is that optical reflectivity only probes the surface to a depth of several atomic layers in a metal. This is quite close to the depth probed by tunneling, which is a coherence length, ξ_0. ξ_0 is presumably some tens of angstroms in our films. The reasoning behind this reflectivity rationale is reflected in the excellent correlation we have observed between reflectivity at 850 nm and the quality of the tunneling characteristic of junctions fabricated from those films [4]. The optical reflectivity at 850 nm also correlates very well with the transition temperature. The very best junctions are fabricated on NbC_xN_y samples having reflectivity > 85 percent at 850 nm.

SECTION 3
DEVICE RESULTS

There are three distinct Josephson device types that have been fabricated under this contract. Two consist of NbC_xN_y lower electrodes and Nb counterelectrodes and use either the composite sputtered aSi barrier, or an n type CVD Ge barrier. The other category of devices are those using NbC_xN_y for both electrodes, which is our ultimate goal. The NbC_xN_y/Nb devices are viewed as a useful subgoal in fabricating all-NbC_xN_y devices. Since SRC has extensive experience with all-Nb devices, it is possible to concentrate on the improvement of the lower electrode and barrier. This objective has been realized, and excellent quality Josephson junctions with the NbC_xN_y/Nb structure have been fabricated using both the aSi and the Ge barrier. Recent activity has thus centered on the problem of fabricating devices with these barriers and having NbC_xN_y counterelectrodes. This section of the report will discuss these three major device types separately.

3.1 NbC_xN_y/aSi/Nb Devices

Under previous NRL contract support this device type had already been developed to a fairly high level [3]. It had been found that a lower power sputter etch resulted in improved I_oR and V_g. Previously sputter etches were done at 500 W for 5 minutes, the new technique used a 20 W sputter etch for a full hour. In the interest of saving time this has been changed to 100 W for 5 minutes without any deterioration in device quality. It is fairly certain that the Ar bombardment during high power sputter etching amorphotizes the NbC_xN_y surface to deeper levels. The Japanese group at Ibaraki found that this amorphous layer [5] led to a poor less dense oxide in the tunneling barrier. In our case, the tunneling barrier is deposited aSi (or CVD Ge) so that the deterioration may be due to degradation of the NbC_xN_y material next to the barrier.

The other improvement previously made was the use of the composite barrier that was originally developed on all-Nb junctions. This barrier

-9-

consists of a thin aSi layer, followed by a thicker hydrogenated aSi layer (aSi:H) and then another thin unhydrogenated aSi layer. The purpose of the two unhydrogenated aSi layers is to prevent the hydrogenated layer from "poisoning" the niobium electrodes. It is not clear that hydrogen would "poison" NbC_xN_y (especially since NbC_xN_y is deposited in a CH_4 partial pressure); nonetheless, for purposes of comparison and expediency, this composite barrier (aSi/aSi:H/aSi) was carried over to the NbC_xN_y/Nb structure. The thickness of the aSi:H was reduced to 3/4 that used for all-Nb junctions in order to compensate for the increased barrier height of the NbC_xN_y/aSi interface [3]. Otherwise the same procedure was used. Typically the aSi/aSi:H/aSi depositions are done for 15 seconds, 45 seconds and 15 seconds respectively at a V_{csb} of 640 volts, which results in a power of ~ 100 watts. The depositions are done at a pressure of 8 mT Ar, to which a partial pressure of 0.5 mT H_2 is added for the hydrogenated layer. All barriers receive a 150°C 1/2 hour O_2 thermal treatment before being reinserted into the vacuum system for the Nb counterelectrode deposition. Niobium counterelectrode deposition and device completion using the SNAP process are identical to previously published techniques used for all-Nb devices.

The composite barrier yielded the same results on both NbC_xN_y and Nb base electrodes: The I_oR product increased and subgap leakage decreased dramatically. What was _not_ done under the previous contract was to combine the lower power sputter etch with the composite barrier. This has now been done, and the result combines the improvements noted for both of those process modifications. An I-V curve is shown in Fig. 3. The relevant device parameters are: I_oR = 1.9 mV, V_m = 70 mV, V_g = 3.8 mV and ΔV_g = 0.4 mV in a current density range of 50-700 A. The base electrode was NN294, deposited at NRL. This film had very high reflectivity, R = 88 percent at 850 nm. It is interesting that this film was unusual in having two NbN phases present, as evidenced by the X-ray diffraction results. This did not affect I_oR or V_m, both of which are excellent, but it is possible that ΔV_g, which is relatively large, was affected. Further systematic study will be needed to resolve this point. The available quality in these junctions is suitable for any application requiring a tunnel junction.
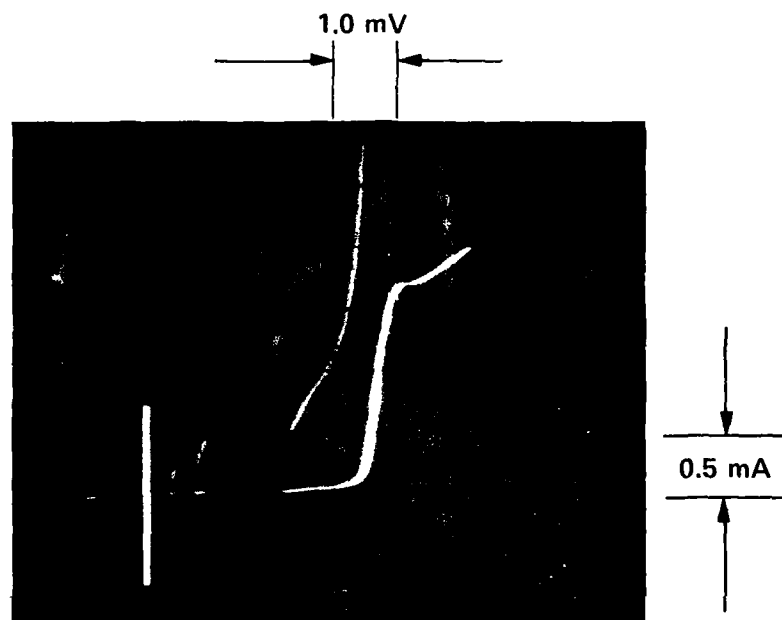
FIG. 3 A high quality NbC_xN_y-aSi:H-Nb device using NRL
supplied NbC_xN_y.

-11-

Figure 4 is a device fabricated from SRC deposited NbC_xN_y. The barrier and counterelectrode were deposited in the same run as the device of Fig. 3, illustrating how the characteristics can vary with base electrode material.

3.2 NbC_xN_y/Ge/Nb Devices

The results on this device type have been written up for submission to Applied Physics Letters. This preprint has been included as the Appendix of this report.

3.3 All-NbC_xN_y Devices

The fabrication of high quality Josephson tunnel junctions having both electrodes of NbC_xN_y is the ultimate goal of this work, and also the major challenge. The problem is that the counterelectrode material within a coherence length of the barrier is most important in determining the quality of the junction, and for high T_c compound superconductors the first few monolayers deposited typically are of poorer quality (lower T_c, higher resistivity, etc.) than the upper layers of the film. NbN is perhaps the most forgiving of the compound superconductors in this regard; and the Japanese have succeeded in producing all-NbN junction of fair, but not good, quality using a native oxide barrier (they claim that their films contain little or no carbon, and can thus be truly labeled NbN) [5,6]. They found that the best junctions resulted when the substrate was at ambient temperature for the counterelectrode deposition. Raising the substrate temperature, which is generally necessary to produce higher quality NbN, resulted in reduced gap and I_oR. They blamed this on interdiffusion between the oxide barrier and the electrodes. This example points out the quandry in fabricating junctions with compound superconductor counterelectrodes: The high temperatures necessary to produce quality superconducting material are likely to speed processes that result in deterioration of the relatively thin and fragile barrier and the desired sharp/clean interfaces between the barrier and the electrodes.

Another source of heating comes about from our desire to use SNAP

-12-

1.0 mV

0.05 mA
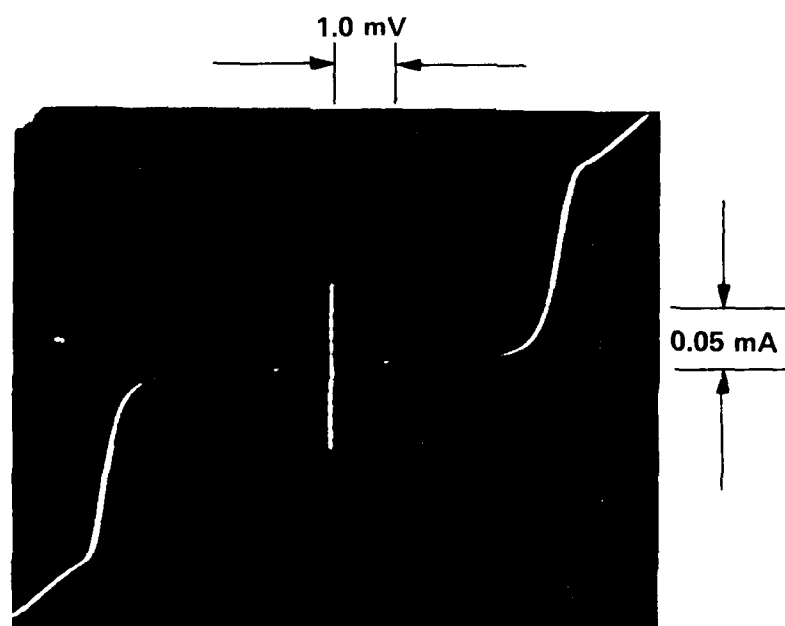
83-687

FIG. 4 A companion device to Fig. 3 fabricated using SRC deposited NbC_xN_y.

type processing for junction isolation. The advantages of doing this are two: First, the barrier is formed on a clean, unpatterned, uncontaminated surface and in principle should be more uniform, reproducible and of higher quality; and second, the same integrated circuit process developed at SRC for all-Nb junctions can be applied to NbC_xN_y junctions. An integrated circuit process is required by the goal of S-I-S mm-wave mixer fabrication. Ideally, one could simply use anodization to isolate junctions, exactly as in Nb SNAP. The problem is that NbC_xN_y does not form a smooth insulating anodic oxide for voltages over ~ 5 V. We have done numerous experiments varying the anodization rate, solution and temperature with the same negative result. Hence, as an alternative procedure for junction isolation we have used thermal oxidation (which requires an SiO_2 mask). Annealing the NbC_xN_y trilayers at 400°C for 30 minutes is sufficient to convert the entire NbC_xN_y counterelectrode (typically 600 A thick) to thermal oxide. This procedure works quite well, and offers good resolution; but even if the NbC_xN_y counterelectrode can be deposited at low temperature, the sample still has to be subjected to a relatively high temperature for junction isolation.

One clue to the resistance of a given barrier to heating can be gained by annealing junctions at elevated temperatures and looking for changes in the electrical characteristics. For our all-Nb junctions with the plain aSi barrier the critical current becomes larger when annealed for ~ 1/2 hour at 200°C. At lower temperatures they are stable. For the composite barrier the comparable temperature is 150°C. Similar behavior is exhibited by NbC_xN_y/Nb junctions with the same barriers. It can be postulated that the presence of a NbC_xN_y counterelectrode would yield a more stable junction than the Nb counterelectrode due to the greater chemical stability of NbC_xN_y (inferred from annealing NbC_xN_y films coated with SiO_2, Si and Ge at high temperatures and looking for changes). It is equally reasonable to infer a breakdown of the barrier itself and/or the superconductor/barrier interfaces.

During the previous year of this contract a NbC_xN_y/aSi/NbC_xN_y junction with a Nb wiring layer, and with S-I-S tunneling characteristics was

-14-

fabricated. The gap voltage was very low, ~ 3 mV, and the subgap leakage was very large; but the fact that it was definitely S-I-S was taken as encouraging evidence that the aSi (noncomposite barrier) can at least partially survive the 400°C thermal oxidation (the counterelectrode was done at "ambient" temperature at NRL, ~ 425°C). This result has not yet been reproduced, although a few attempts have been made.

One possible confound in the above device is that an inadvertent junction could be formed between the top surface of the NbC_xN_y counterelectrode and the subsequent niobium wiring layer. To check on this a NbC_xN_y sample was processed with no tunneling barrier. The desired result, superconducting shorts, was ob .rved.

Due to the fact that the CVD Ge barrier is deposited at 380°C, it can be postulated that it might be more temperature resistant than a barrier formed at lower temperatures. Attempts were made to complete devices of this structure, but insufficient time was available. It is our opinion that this structure represents the best possibility for fabricating all-NbC_xN_y junctions with very high quality tunneling characteristics.

SECTION 4
MIXER RESULTS

All-niobium S-I-S mixer chips designed at GISS have been successfully fabricated and tested. The fabrication is identical to our logic fabrication process [7] with the exception that no resistors are used. Testing was done at GISS. The chips supplied were lower resistance than desired, and also had higher leakage than our "best" junctions. Nonetheless, GISS observed a noise temperature of 60 K and a conversion loss of 5 dB. They consider these results fully comparable to their results with Pb-alloy junctions.

GISS also found that a major source of conversion loss (~ 2 dB) was due to the Cr-Au choke structures they have been using. We have recently delivered to GISS choke structures fabricated from niobium, with small gold pads in the bonding areas.

GISS has developed a second generation mixer design which uses a series capacitance and inductance to shunt the junction detector array. They expect much broader bandwidth coupling of the rf to the mixer with this design, and consequently improved performance. This design has been digitized at SRC but masks have not been fabricated.

SECTION 5
CONCLUSIONS

Excellent progress has been made on all aspects of this project except one: The fabrication of all-NbC_xN_y junctions of good electrical quality using integrated circuit compatible fabrication techniques. As discussed in the section on all-NbC_xN_y devices there are fundamental reasons why this is a difficult problem. The problem is not intractable, as demonstrated by our poor quality S–I–S result, NRL results [8] and the Japanese results [5,6]. Not all the above results are IC compatible, but they demonstrate that the basic problem of junction fabrication can be overcome.

Although the production of good quality NbC_xN_y appears to be in hand, the quality is evaluated in terms of the suitability of the material for base electrodes. It is quite possible that as future work on all-NbC_xN_y devices continues, the deposition parameters for NbC_xN_y will have to be adjusted in different ways to produce high quality for the counterelectrode.

-17-

SECTION 6
REFERENCES

1. S. Wolf, I. Singer, E. Cukauskas, T. Francavilla, and E. Skelton, J. Vac. Sci. Technol., 17 (1980) 411.

2. E.J. Cukauskas, J. Appl. Phys., 54 (1983) 1013.

3. D. Jillie, H. Kroger, and L. Smith, Final Report on NRL Contract No. N00014-81-C-2525, Sept. 1982.

4. D. Jillie, H. Kroger, L. Smith, E. Cukauskas and M. Nisenoff, Appl. Phys. Lett., 40 (1982) 747.

5. M. Igarashi, M. Hikita and K. Takei, Proceedings of the International Conference on Cryogenic Materials, Colorado Springs, CO, USA, August 1983.

6. A. Shoji, F. Shinoki, S. Kosaka, M. Aoyagi and H. Hayakawa, Appl. Phys. Lett., 41 (1982) 1097.

7. D. Jillie, L.N. Smith, H. Kroger, L. Currier, R. Payer, N. Potter, and D. Shaw, IEEE J. Solid State Circuits, (1983).

8. E.J. Cukauskas, M. Nisenoff, H. Kroger, D. Jillie, and L. Smith, Proceedings of the International Conference on Cryogenic Materials, Colorado Springs, CO, USA, August 1983.

SECTION 7
APPENDIX

JOSEPHSON TUNNEL JUNCTIONS WITH CHEMICALLY VAPOR
DEPOSITED POLYCRYSTALLINE GERMANIUM BARRIERS

H. Kroger, D.W. Jillie, L.N. Smith,

L.E. Phaneuf, C.N. Potter and D.M. Shaw

Sperry Research Center

E.J. Cukauskas and M. Nisenoff

Naval Research Laboratory

Abstract

High quality Josephson tunnel junctions have been fabricated whose tunneling barrier is polycrystalline germanium chemically vapor deposited on a NbN base electrode and covered by a Nb counterelectrode. These junctions have excellent characteristics for device applications: values of V_m (measured at 2 mV and 4.2 K) ranging between 35-48 mV; ideal threshold curves; a steep current rise at the gap voltage; and current densities in the vicinity of 1000 A/cm^2.

This letter reports the fabrication of high-quality Josephson tunnel junctions whose tunnel barrier is a chemically vapor deposited (CVD) polycrystalline layer. The lower electrode is niobium nitride deposited by reactive sputter deposition, which has recently been described in detail.[1] The barrier is germanium deposited by pyrolysis of germane[2] at 380°C in a room pressure reactor. The upper electrode is niobium deposited by dc-magnetron sputtering. The mutual isolation of devices is obtained by the selective niobium anodization process (SNAP).[3]

The NbN films used in these experiments are deposited at the Naval Research Laboratory and are given a low power sputter cleaning in argon at Sperry Research Center just before the wafer is introduced into the CVD reactor.[4]

The germanium layers are deposited in a conventional, cold wall, horizontal flow CVD reactor whose operation (heating, introduction of gases, etc.) is automatically sequenced. The substrate is placed on a graphite susceptor which is inductively heated and the wafer is brought up to the deposition temperature in a pure argon atmosphere. The premixed gases which are introduced for film growth are argon, germane and arsine for the devices described here. Total flow is 55 cm^3/min, with 3.6 percent of the flow being GeH_4 and 0.027 percent being AsH_3.

The deposition time of these barrier layers was about two minutes. We estimate the thickness to be 30-60 A based upon the growth rates and

-22-

thickness measurements of thicker films. The large uncertainty in the barrier

thickness arises from a suspicion that the initial growth rate is smaller than

the limiting growth rate (~ 25-30 A/min) obtained for thick (> 0.1 μm) layers.

Following the deposition of the polygermanium layer, the layers are

exposed to an O_2 atmosphere at 400°C for 20 minutes. This is a

precautionary step taken to oxidize the base electrode through pinholes in the

barrier, and the (unconfirmed) possibility that such pinholes exist. No

visual change in the barrier takes place during the oxidation treatment.

Immediately before the Nb counterelectrode is deposited, the barrier is

cleaned by sputter etching at a low applied power using the same techniques as

previously described.[5,6]

We infer from examination of thicker layers (0.5 - 2.0 μm) that the

germanium films are crystalline. X-ray diffraction shows that the films have

a mixed (110) and (111) orientation. The magnitude of the room temperature

resistivity is less than 1 Ω-cm, which is considerably lower than one would

expect for amorphous germanium. Also the resistivity of these layers

initially decreases as the temperature is lowered below room temperature,

which would not be expected for amorphous materials. These n-type layers are

not degenerately doped and become bulk insulators at 4.2 K.

We observed a slower growth rate of both germanium and silicon with

the addition of either phosphine or arsine to produce n-type layers; a similar

reduction in growth rate of CVD amorphous n-type silicon has been observed by

Taniguchi et al.[7] The slower growth rate, rather than the n-type doping, may be more important for practical considerations since the thickness of a more slowly grown layer should be more easily controlled.

Figure 1 displays the current-voltage characteristics of a 10 μm x 10 μm square device at 4.2 K. The critical current density J_c is ~ 560 A/cm^2. The superconducting energy gaps are 2.65 mV for the NbN electrode and 1.35 mV for the Nb electrode. The differential resistance at zero bias of the quasiparticle characteristic is ~ 100 times that of the normal resistance of these devices. The V_m parameter (product of I_c and the subgap resistance measured at 2 mV) is 41 mV for this particular device. The range of observed V_m on this wafer was from 35-48 mV. The product of I_c and the normal resistance is 1.8 mV. The jump in the quasiparticle current is relatively abrupt, with the change from 30 percent to 80 percent of the full gap current spanning approximately 50 μV.

Figure 2 displays the threshold curve obtained from another device whose J_c ~ 1100 A/cm^2. Note that under even a four-fold expansion of the current scale the minima are close to zero. Moreover, the ratios of the heights of the secondary maxima to the zeroth order maximum are as expected for a $|\sin x/x|$ curve to within experimental accuracy. (We estimate that the Josephson penetration length is comparable to the device dimensions.) This indicates that the Josephson current density is extremely uniform over the entire area of the device. This is a comforting observation since the

-24-
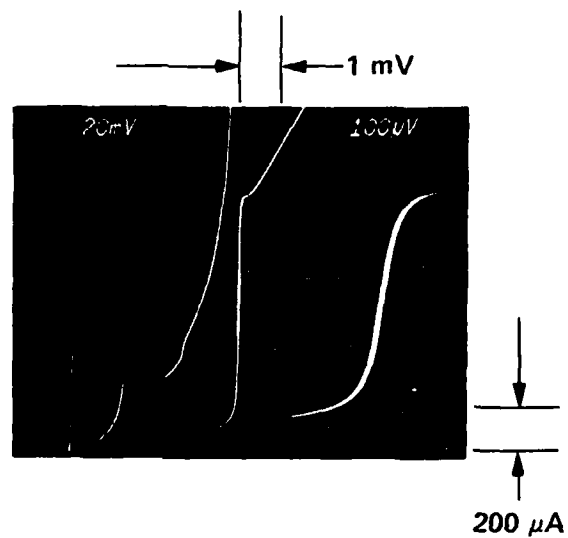
FIG. 1 I-V characteristics of a NbN-polygermanium-Nb at 4.2 K.
Also shown at 10 times expansions of the current and
voltage scales to show more clearly the subgap current
and jump in current at the gap, respectively. (The origin
of the 10 times expanded voltage trace is not on the
figure.)

FIG. 2 Threshold curve (I_c vs. applied magnetic field) of a
companion device. Also shown is a four times expansion
of the current. Threshold curve is almost exactly a
$|\sin x/x|$ function.

200 μA

-26-

discrete grains of a polycrystalline film could result in poorer thickness
uniformity than an amorphous layer. We assume that the uniformity implies a
very small grain size.

We have fabricated similar structures with a CVD polycrystalline Si
barrier. These devices had fairly good threshold curves but large subgap
leakage currents. We are not certain whether the superior results obtained
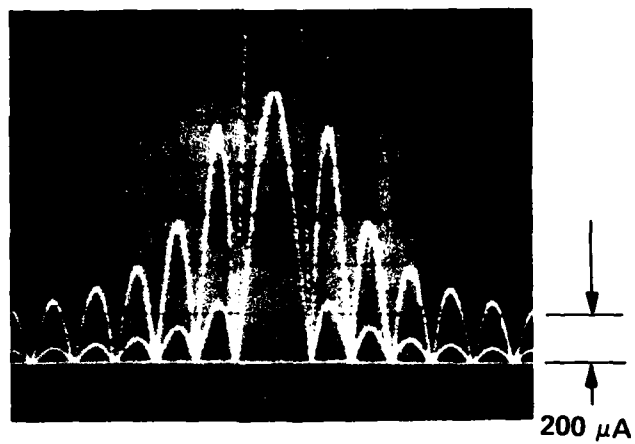with the germanium barriers are intrinsic to this material or if this merely
reflects evolution in technique or quality of the NbN base electrode
material. We have previously observed that the device quality of NbN-aSi-Nb
junctions is extremely sensitive to the quality of the NbN, especially its
transition temperature T_c and its optical reflectivity at 850 nm.[4,8]

We have also fabricated devices with degenerately doped p-type Ge
layers which resulted in both Josephson and super-Schottky barrier devices,[9]
qualitatively similar to those fabricated by Huang and Van Duzer on
degenerately boron-doped single crystal silicon membranes.[10] The behavior
of our p^+ Ge barrier devices will be more fully described in subsequent
publications.

The use of niobium nitride as a base electrode, rather than niobium,
is crucial to the successful fabrication of this type of device structure,
because Nb reacts with the barrier at the elevated temperatures required for
the CVD of both Ge and Si.[11] We observed that reactions between Si and Nb
occur not only for CV deposited Si, but also when attempting to crystallize

-27-

amorphous silicon layers previously deposited on niobium. At about 300°C, a blue layer forms whose color does not appear to be related to interference and a disruption of the Si-Nb interface is observed. On the other hand, CVD layers of Si and Ge deposited on NbN substrates do not show any obvious signs of reaction even at temperatures as high as 800°C and 600°C, respectively.[12]

In summary we have described the fabrication and the electrical characteristics of NbN-cGe-Nb Josephson tunnel junctions whose barrier is deposited by chemical vapor deposition. While these characteristics are easily good enough for many digital and S-I-S mixer applications it may not be the quality of the devices which is most significant. (Indeed, these structures are not the "best" we have ever fabricated.) Rather, it may be that the method of barrier deposition is more important. The many person-years invested in developing chemical vapor depositions for the semiconductor industry could be further exploited to improve the manufacturability of these devices. Finally, because of the high deposition temperature, it may be possible to use thermal oxidation to isolate an upper niobium nitride electrode in a variation of SNAP previously suggested,[3] without risking disruption of the barrier.

References

1. E.J. Cukauskas, J. Appl. Phys., 54, 1013, (1983).

2. L.H. Hall, J. Electrochem. Soc., 119, 1593-1596, (1972).

3. H. Kroger, L.N. Smith, and D.W. Jillie, Appl. Phys. Lett., 34, 280, (1981).

4. D.W. Jillie, H. Kroger, L.N. Smith, E.J. Cukauskas and M. Nisenoff, Appl. Phys. Lett., 40, 747, (1982).

5. L.N. Smith, J.B. Thaxter, D.W. Jillie and H. Kroger, IEEE Trans. Magn., MAG-18, 1571, (1982).

6. H. Kroger, L.N. Smith, D.W. Jillie and J.B. Thaxter, IEEE Trans. Magn., MAG-19, 783, (1983).

7. M. Taniguchi, Y. Osaka and M. Hirose, J. Electronic Mater., 8, 689, (1979).

8. E.J. Cukauskas, M. Nisenoff, D.W. Jillie, H. Kroger and L.N. Smith, IEEE Trans. Magn., MAG-19, 831, (1983).

9. D.W. Jillie, H. Kroger, L.N. Smith, E.J. Cukauskas and M. Nisenoff, Bull. Am. Phys. Soc., 27, 639 (1982).

10. C.L. Huang and . Van Duzer, IEEE Trans. Electron Device, ED-23, 579, (1976).

11. H. Kroger, C.N. Potter and D.W. Jillie, IEEE Trans. Magn., MAG-15, 488, (1979).

12. H. Kroger, U.S. Patent 4,220,959, 1980.

Naval Electronics System Command
Washington, D.C.   20361

      Attn: Mr. R. Wade (Code 614)   1
      Attn: M. J. P. Letelier (Code 614)   1

Office of Naval Research
800 No. Quincy Street
Arlington, Va.   22217

      Attn: Mr. E. A. Edelsack (Code 414)   1
      Attn: Mr. M. Yoder (Code 414)   1

Army Research Office
Box CM, Duke Station
Durham, N.C.   27706

      Attn: Dr. C. Bogosian   1

Air Force Office of Scientific Research
Bolling Air Force Base
Bldg. 410
Washington, D.C.   20332

      Attn: Dr. M. Swerdlow   1

Defense Documentation Center
Cameron Station
Alexandria, Va.   22314   12

Naval Research Laboratory
4555 Overlook Road, S.W.
Washington, D.C.   20375
      Attn: Code 1231   1
      Attn: Code 6854   10
      Attn: Code 2627   6

Advisory Group on Electronics
201 Varck Street
New York, N.Y.   10014

      Attn: Working Group B   1

Defense Advanced Research Agency
1400 Wilson Avenue
Arlington, Va.   22209

      Attn: Dr. A. J. Bruckheim   1

Naval Coastal Systems Laboratory
Panama City, Fla.   32401

       Attn: Dr. L. Ishol   1

U. S. Army Electornic Technology and Device Laboratory
DRSEL-TL-ES
Fort Monmouth, N.Y.   07703

       Attn: Dr. F. Rothwarf   1

Laboratory for Physical Sciences
4928 College Ave
College Park, Md.   20740

       Attn: Dr. N. Welker   1

National Bureau of Standards
Cryoelectronics Section
Electromagnetic Technology Division
Boulder, Co.   80302

       Attn: Dr. R. Harris   1
       Attn: Dr. C. Hamilton   1

National Bureau of Standards
Gaithersburg, Md.   20234

       Attn: Dr. L. Holderman   1

Prof. R. Buhrman
Department of Physics
Clark Hall
Cornell University
Ithaca, N.Y.   14853   1

Prof. M. R. Beasley
Department of Physics
Stanford, CA   94305

Prof. B. S. Deaver, Jr.
Department of Physics
University of Virginia
Charlottesville, Va.   22901   1

Prof. P. Richards
Department of Physics
University of California
Berkeley, CA   94720

Prof. D. E. Prober
Recton Center
Yale University
New Haven, CT   06520   1

Prof. M. Tinkham
Department of Physics
Harvard University
Cambridge, MA   02138   1

Prof. R. Mattauch
Department of Electrical Engineering
University of Virginia
Charlottesville, Va.   22901   1

Sperry Research Center
100 North Road
Sudbury, MA   01776

        Attn: Dr. D. W. Jillie   1
        Attn: Dr. H. Kroger   1

SHE Corporation
4174 Sorrento Valley Road
San Diego, CA   92121   1

        Attn: Dr. W. Black

Texas Instruments
13500 N. Central Expressway
Post Office Box 6015, M/S266
Dallas, TX   75222

        Attn: Dr. F. D. Colegrove   1

TRW, Defense and Space Group
One Space Park
Redondo Beach, CA   90278

        Attn: Dr. A. H. Silver (R1/1086)   1
        Attn: Dr. R. Davidheiser (R1/1086)   1

Westinghouse Research Center
1310 Beulah Road
Pittsburgh, Pa.   15235

        Attn: R. Blaugher   1

-33-

END

FILMED

12-83

DTIC